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Receptivity of a Cryogenic Coaxial Liquid Jet to Acoustic Disturbances

ILASS-Americas 2014

Integrity ★ Service ★ Excellence

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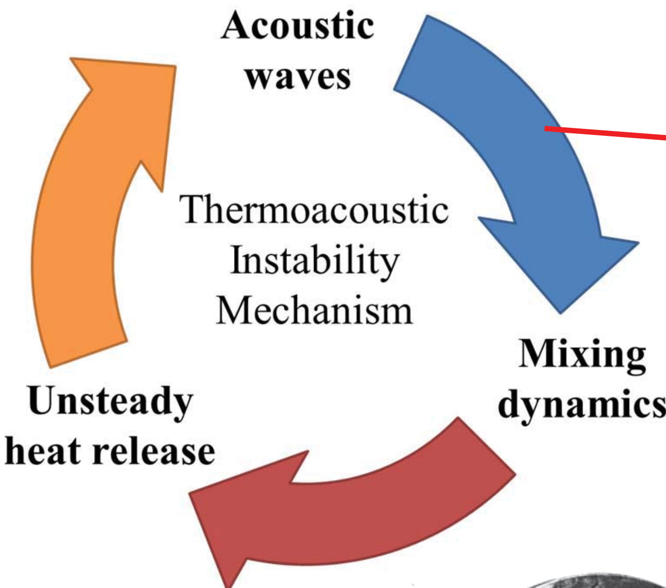
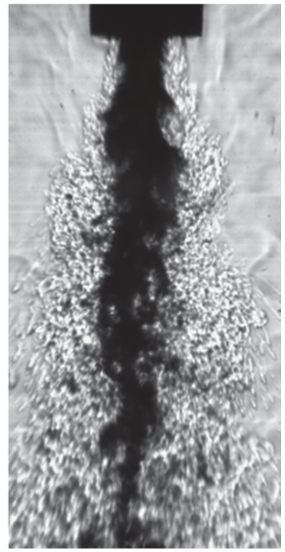
Ivett Leyva, AFRL/RQRE
Doug Talley, AFRL/RQRC

Outline

- Motivation and objectives
- Parameters of the forced coaxial jet
- Experimental facility
- Results
  - Unforced cases
  - Pressure node/antinode forcing
- Conclusions

Motivation: Combustion Instability in Rocket Engines





Objectives

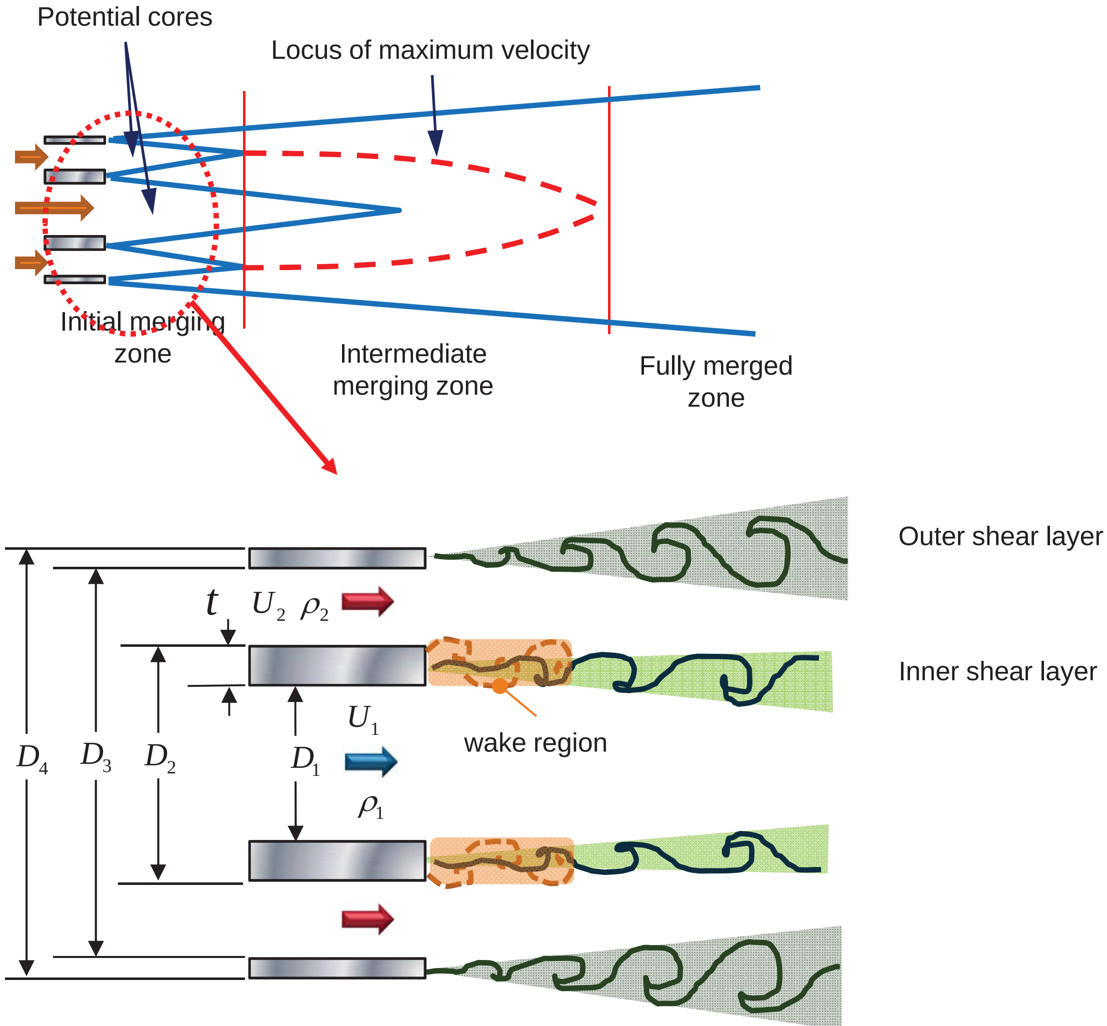
Investigate acoustic receptivity characteristics of a model liquid rocket engine injector

- Dimensionless frequency
- Acoustic amplitude
- Momentum flux ratio
- Location within the mode

“Preferred mode” of the coaxial jet

- Definition of natural frequency of the flow
- Characteristic velocity scale

The Coaxial Jet



Geometry parameters

Area ratio

$$AR = \frac{D_3^2 - D_2^2}{D_1^2}$$

Dimensionless post thickness

$$\frac{t}{D_1}$$

Flow parameters

$$\mathrm{Re}_i = \frac{\rho_1 U_1 D_1}{\mu_1} \qquad \mathrm{Re}_i = \frac{\rho_2 U_2 (D_3 - D_2)}{\mu_2}$$

$$J = \frac{\rho_2 U_2^2}{\rho_1 U_1^2} \qquad r = \frac{U_2}{U_1} \qquad s_1 = \frac{\rho_2}{\rho_1} \qquad s_2 = \frac{\rho_3}{\rho_2}$$

$$We = \frac{\rho_2 U_2^2 D_1}{\sigma}$$

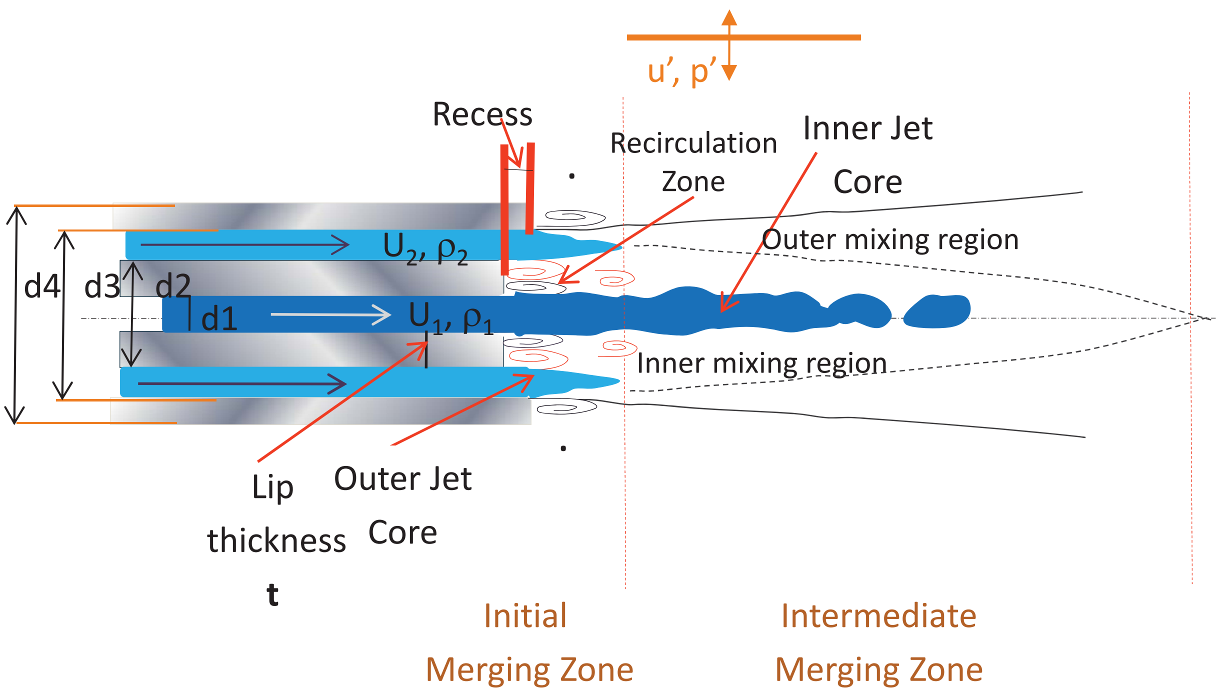
Inflow boundary conditions

- Mean velocity profiles
- RMS fluctuation profiles
- Spectral content

The Forced Coaxial Jet

Very low density ratio regime: $0.005 < \frac{\rho_2}{\rho_1} < 0.1$

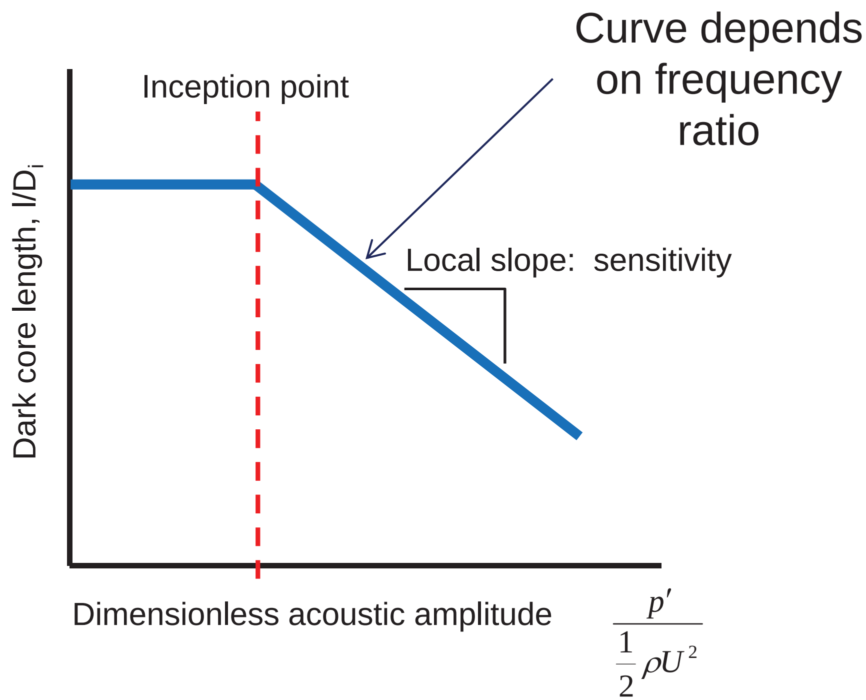
1. **Transverse Acoustic mode from chamber/siren**
   - f=f(c, geometry)
2. **Acoustic modes propellant lines**
   - f~c/2L
3. **Post wake**
   - $St=ft/U_{ch}$
4. **Shear layer instabilities**
   - $St_\theta=f\theta/U_{ch}$
5. **Jet preferred modes**
   - $St=fD_{ij}/U_{ij}$

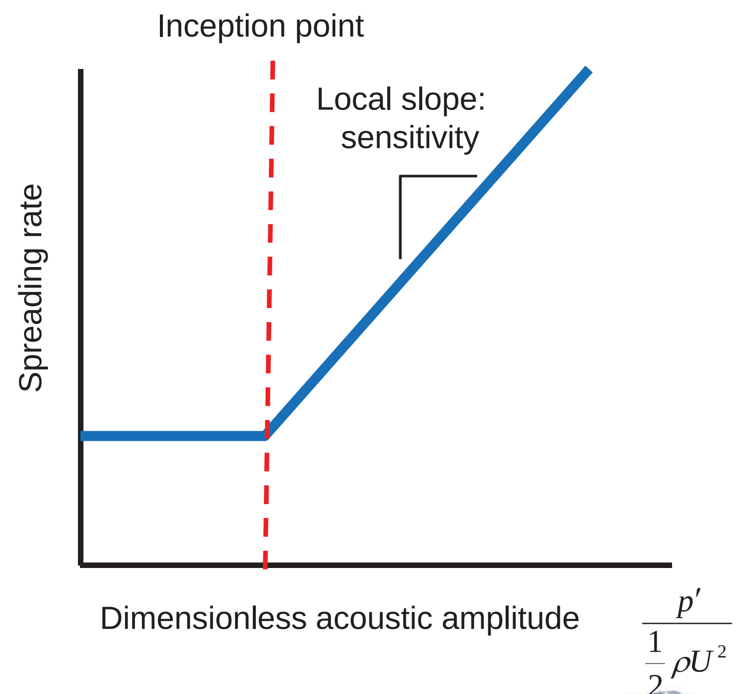


Forcing Characterization

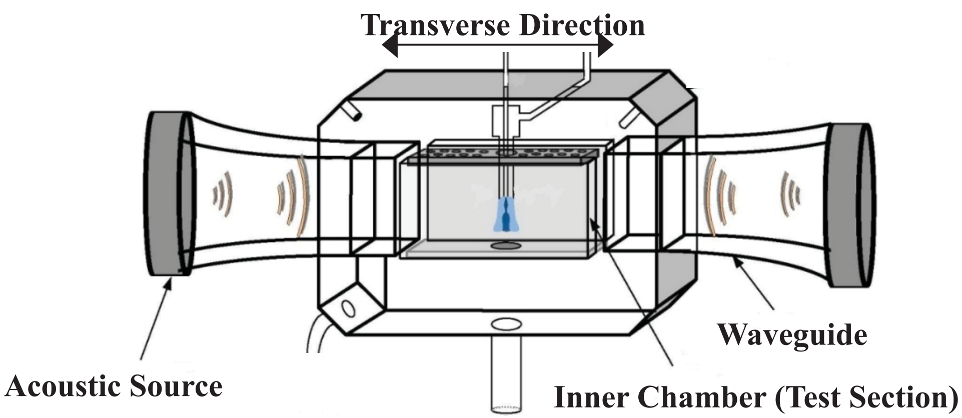
- Shift pressure normalization from chamber pressure to injector dynamic pressure
- Normalize the frequency by the preferred mode of the coaxial jet
- Identify receptivity inception point—threshold for coupling between acoustics and flame

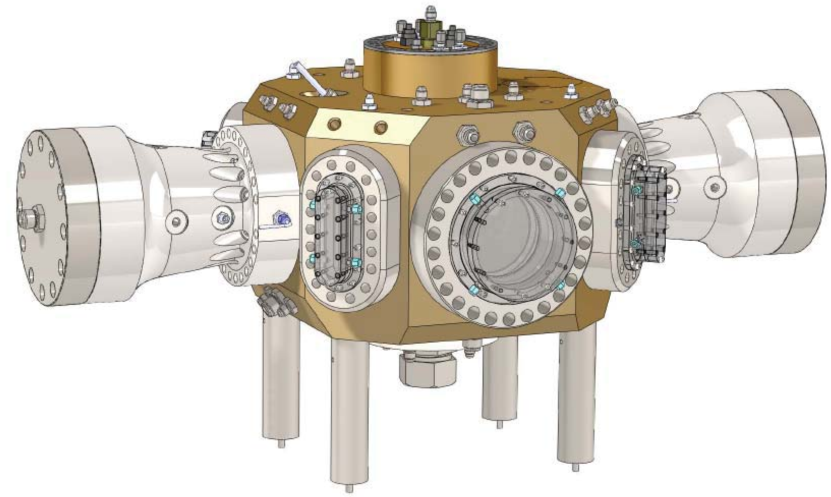
$$P'/\overline{P}_c \rightarrow \frac{P'}{\rho U^2/2} \qquad F = \frac{f_{forcing}}{f_{jet}}$$





Experimental Facility



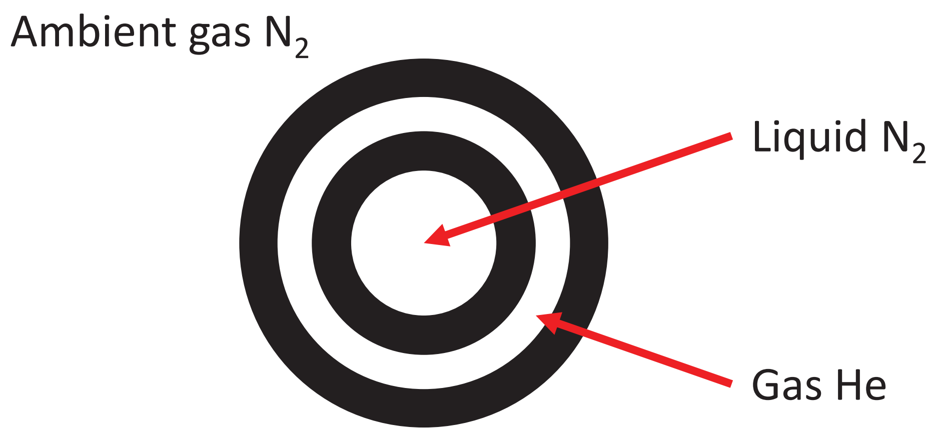


Capabilities

– Cryogenic propellant temperature control with high accuracy (±1 K)
– Sub- and super-critical chamber pressure (p_c up to 10.4 MPa)
– High amplitude acoustic forcing (p'/p_c ~ 0.02)
– Coaxial injector with extended length for fully developed turbulent flow ($l_e/D > 110$)
– High-speed diagnostic tools
  - Pressure transducer(s) natural frequency > 100 kHz
  - Time-series backlit imaging (f > 25 kHz)
  - Off-axis windows for future PIV/PLIF measurements

Experimental Conditions

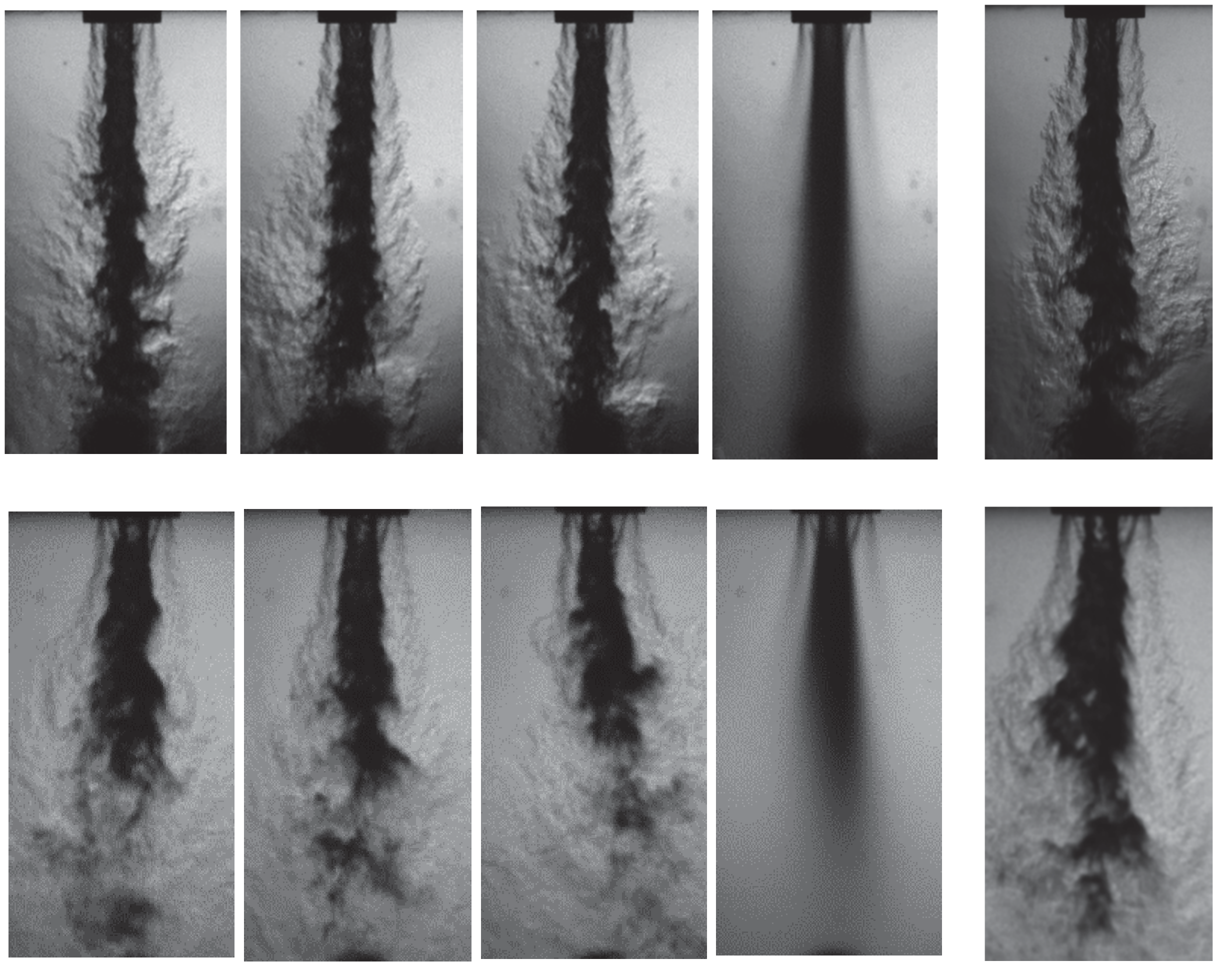
- New injector
  - D_1 = 1.4 mm
  - AR = 1.68
  - t/D_1 = 0.27
- J = 2 and 6
- N_2 inner jet @ 120 K
- Gaseous He @ 275 K
- $Re_1 \sim 1.5\text{x}10^4$
- $Re_2 \sim 1\text{x}10^4$
- Fully-developed turbulent flow conditions
- Chamber pressure 2.8 MPa (400 psi)→ subcritical



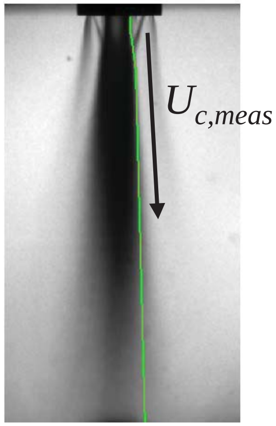
Unforced Cases

J = 2

J = 6



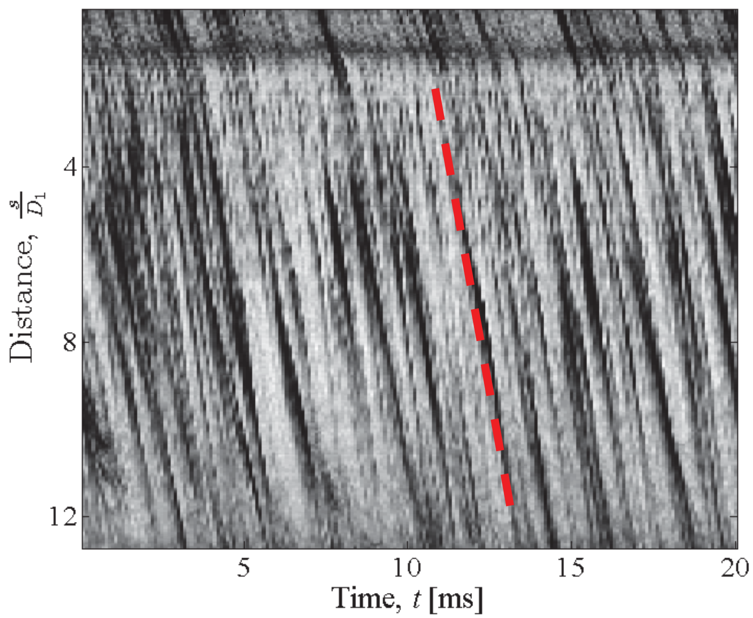
Convection Velocity

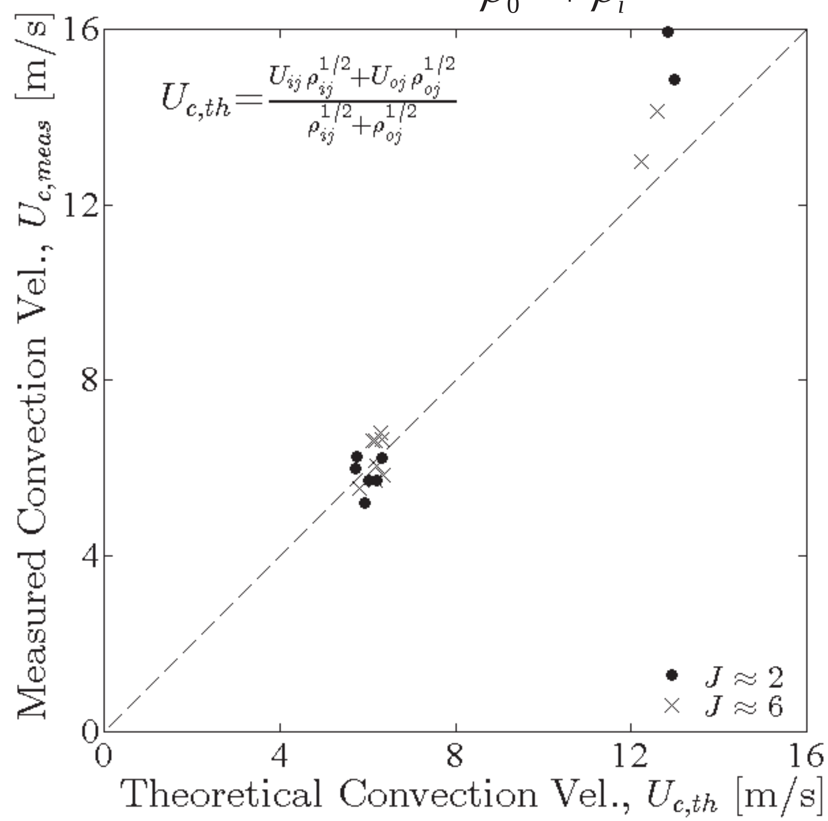


Verify the accuracy of the Dimotakis (1986) expression for shear layer convection velocity for these flow conditions.

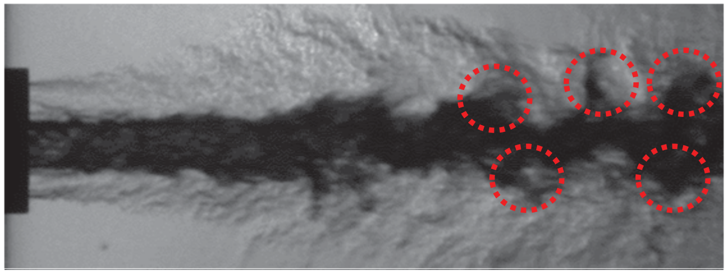
$$U_{c,meas} = \frac{\Delta s}{\Delta t}$$

$$U_{c,th} = \frac{U_o \rho_0^{1/2} + U_i \rho_i^{1/2}}{\rho_0^{1/2} + \rho_i^{1/2}}$$

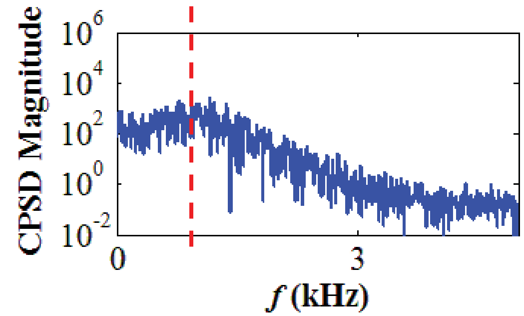




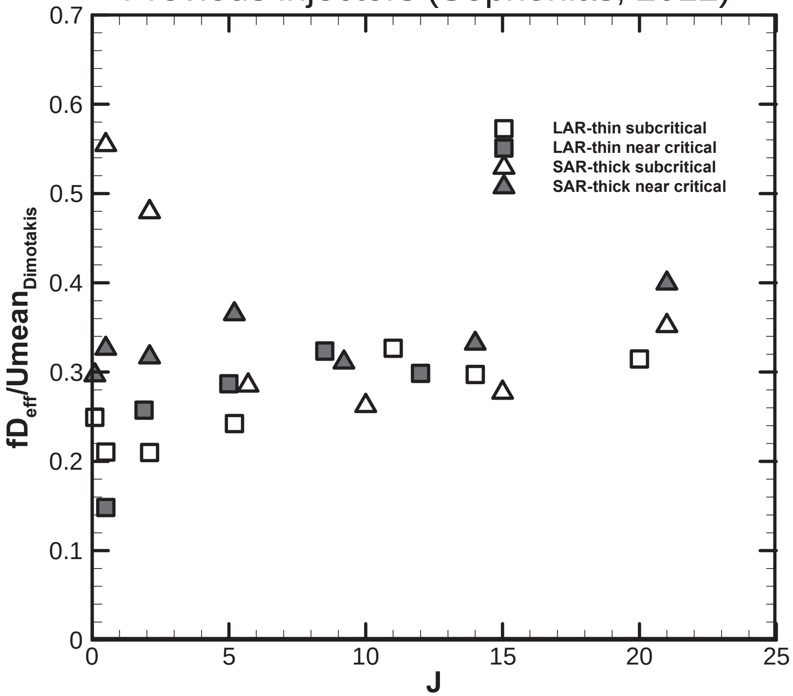
Preferred Mode Frequency



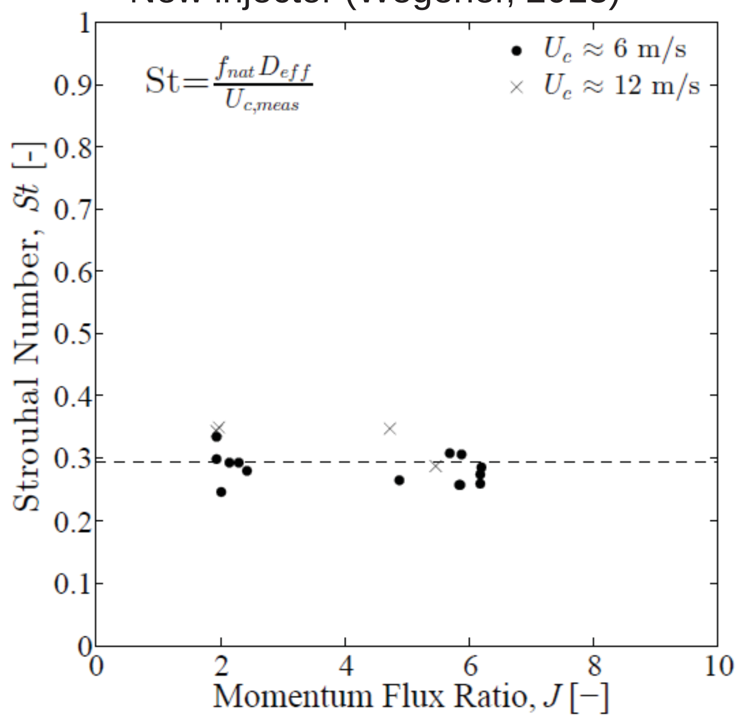
Most energetic convective mode pair from POD



Previous injectors (Sophonias, 2012)



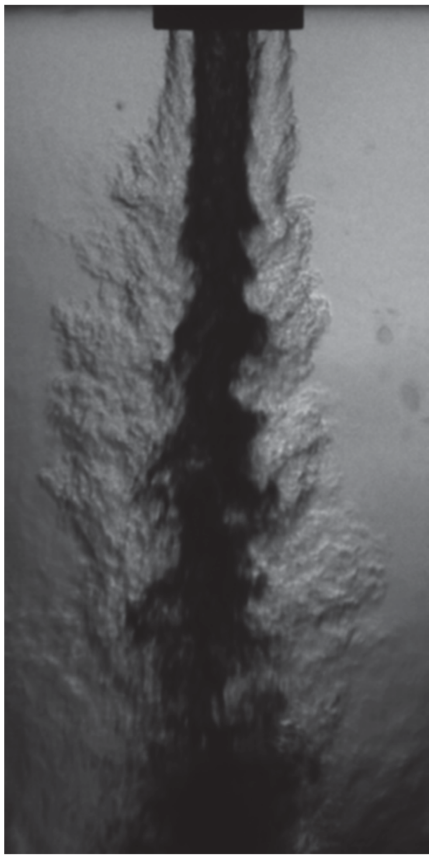
New injector (Wegener, 2013)



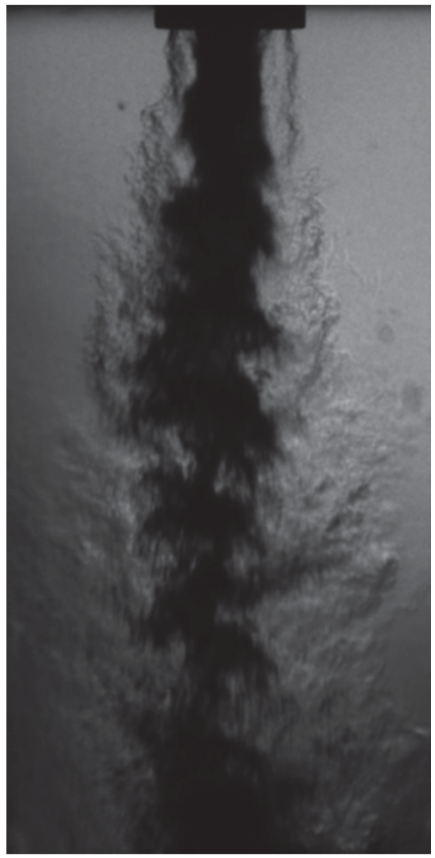
Forced Cases

Representative cases for pressure node and pressure antinode

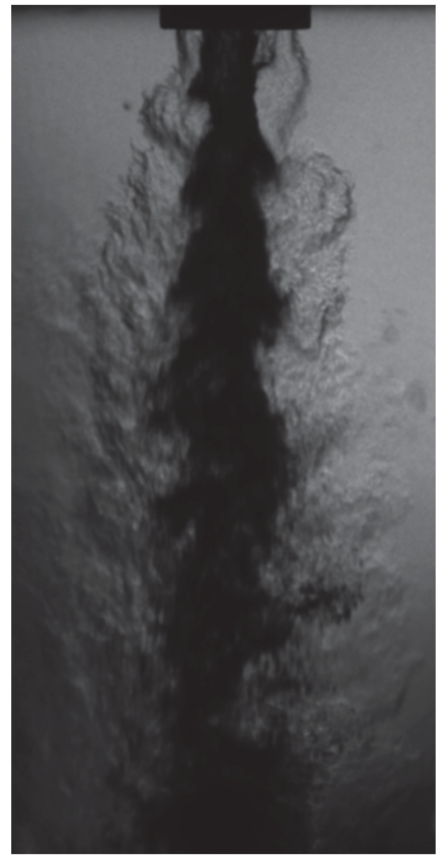
baseline



Pressure antinode

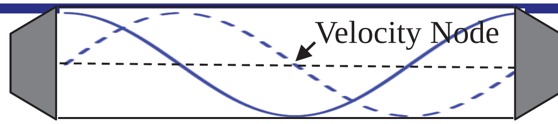


Pressure node

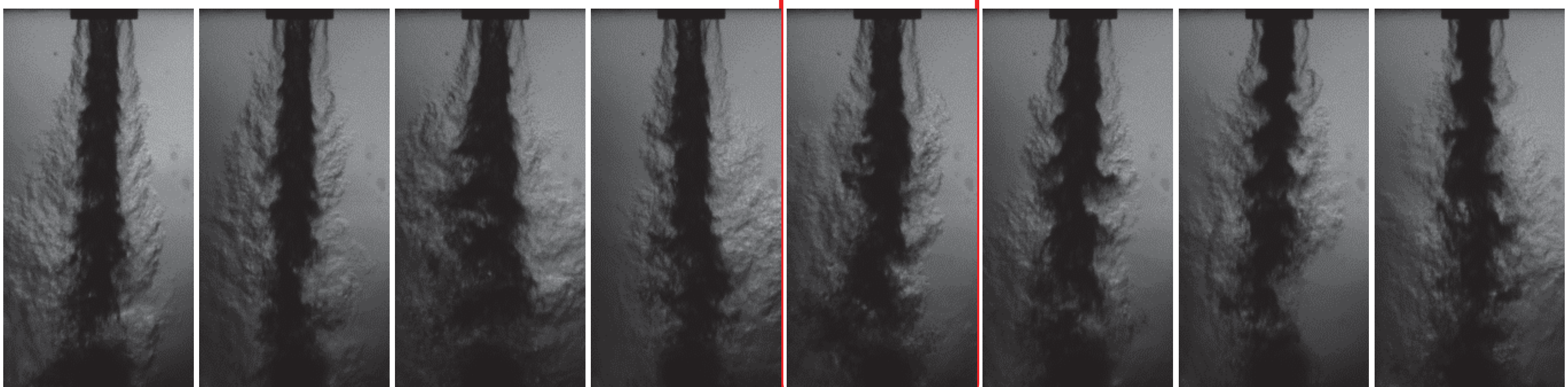


Pressure Antinode Response J = 2

$$A = \frac{p'}{\frac{1}{2}\rho_2 U_2^2}$$



$$F = \frac{f_{forcing}}{f_{jet}} = 2.6$$

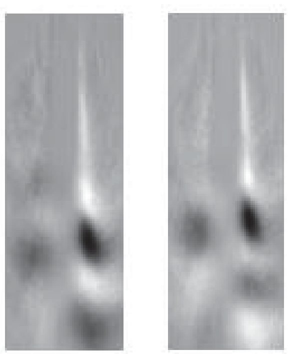


No receptivity

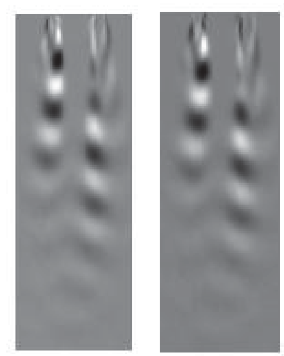
Weak receptivity

High receptivity

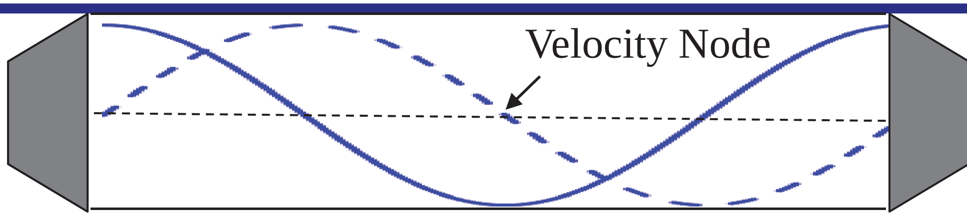
Natural convective POD mode pair

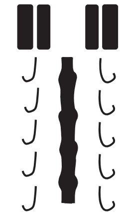


Forced convective POD mode pair



Pressure Antinode Mechanism

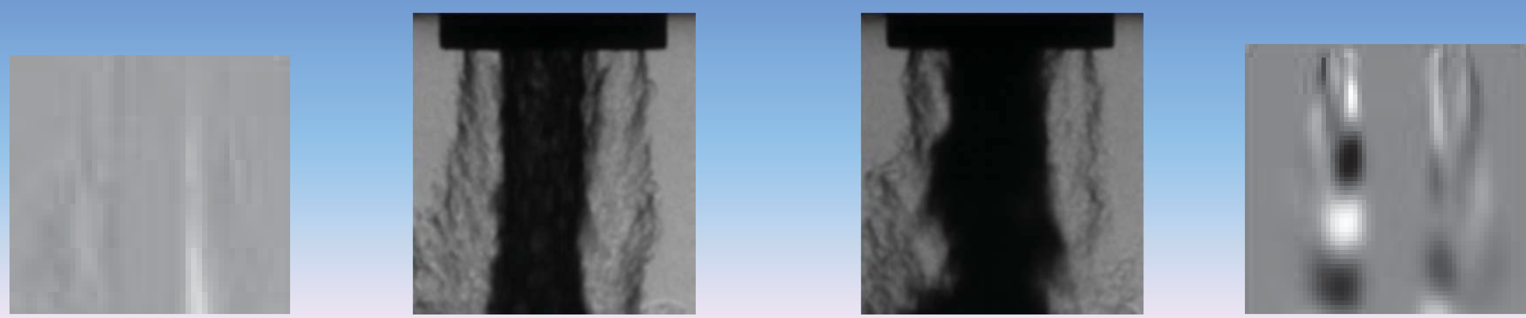




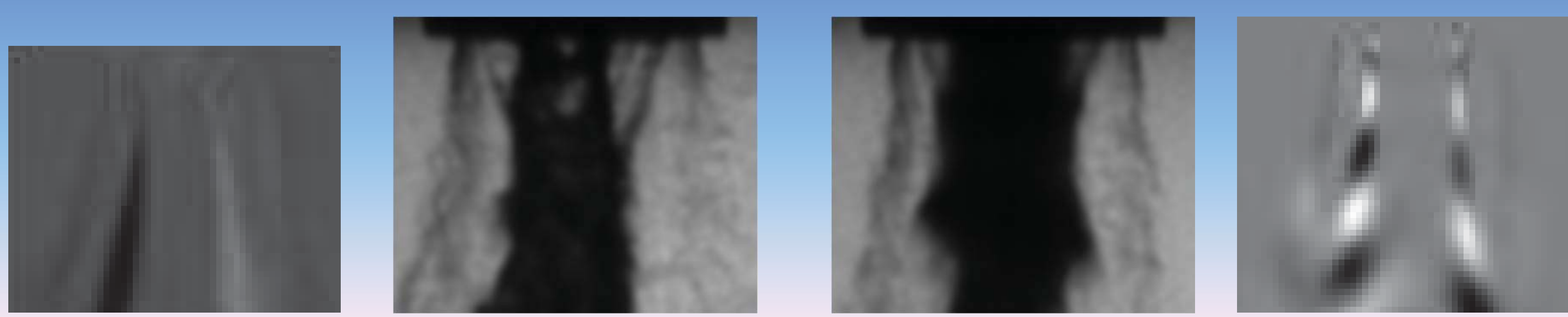
Outer jet mass flow pulsations

POD structure | unforced | Max forcing | POD structure

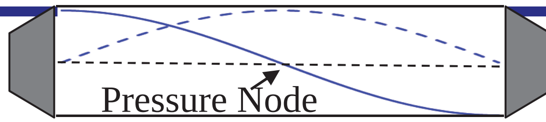
J = 2



J = 6

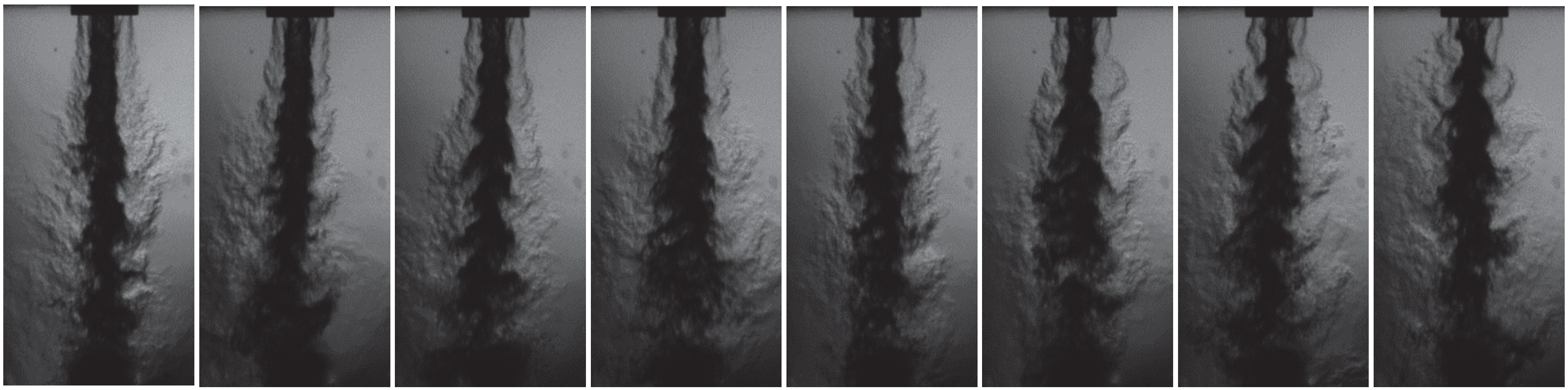


Pressure Node Response J = 2



$$F = \frac{f_{forcing}}{f_{jet}} = 2.6$$

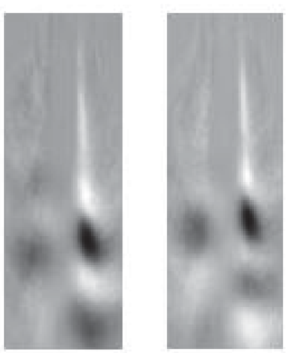
U' = 0 | 0.06 m/s | 0.12 m/s | 0.16 m/s | 0.25 m/s | 0.34 m/s | 0.52 m/s | 0.72 m/s



No receptivity

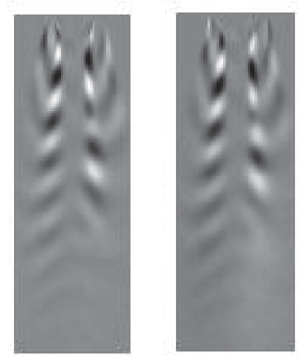
Weak receptivity

High receptivity

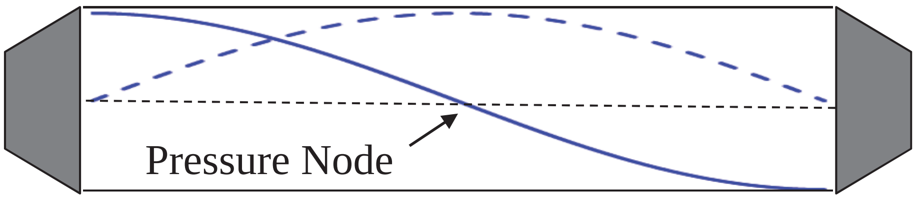


Natural convective POD mode pair

Forced convective POD mode pair

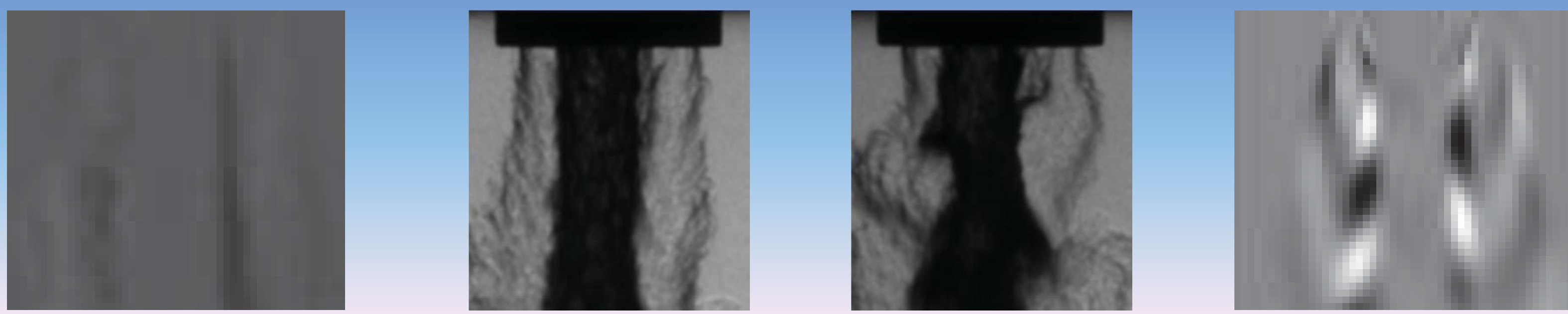


Pressure Node Mechanism

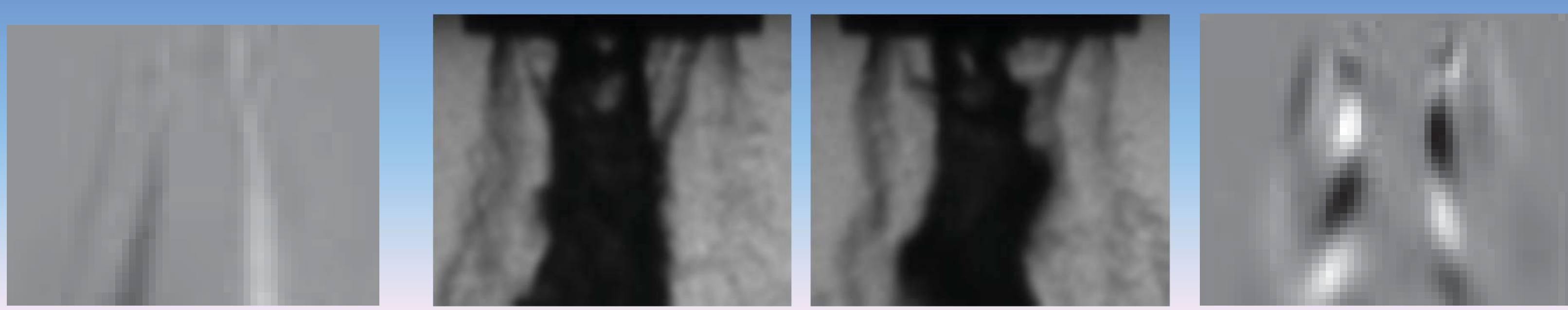


Apparent excitation of antisymmetric mode in the outer jet that drives instabilities in the inner jet

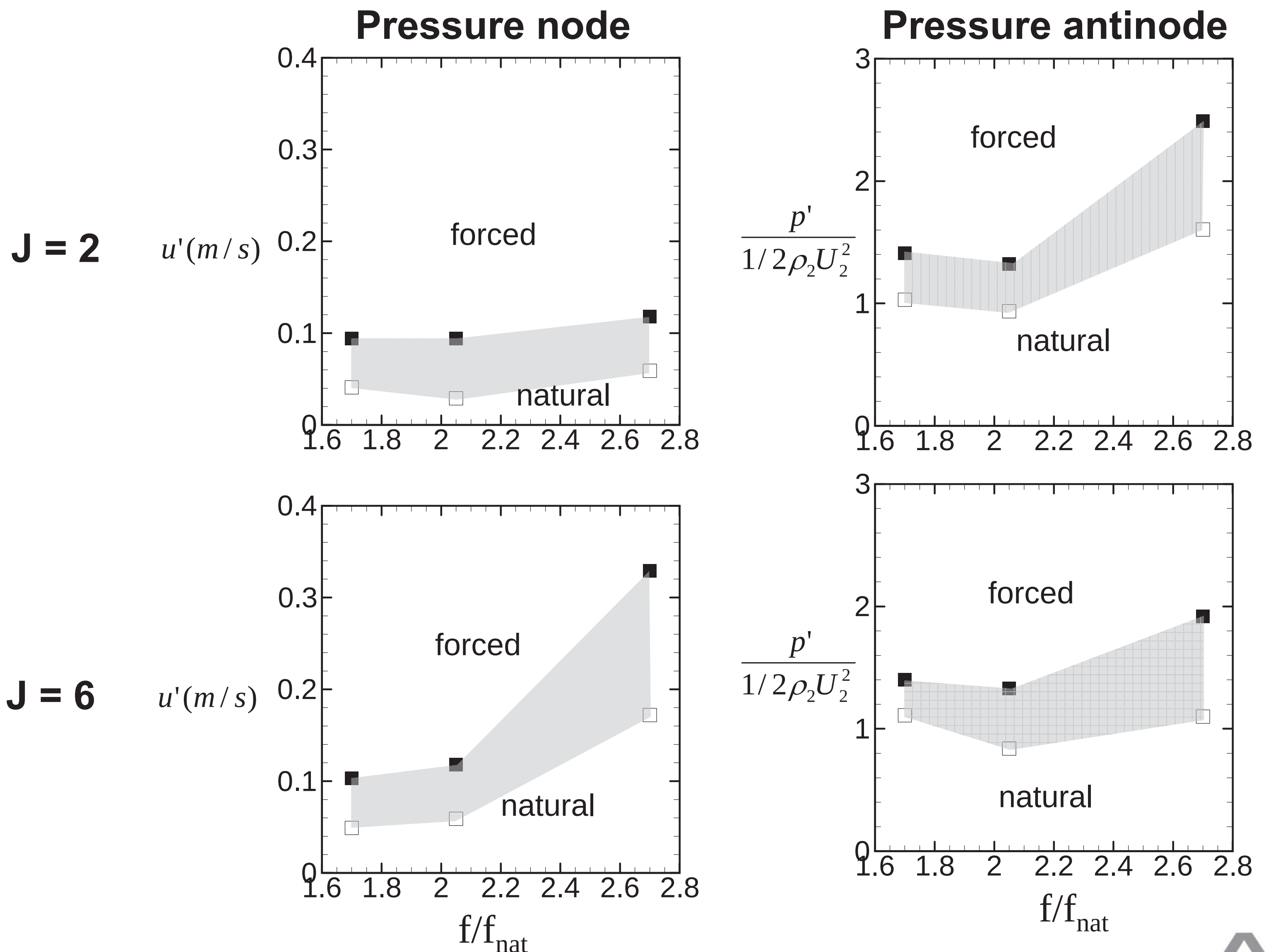
J = 2



J = 6



Receptivity



Summary

- Convection velocity predicted using shear layer model
- Coaxial jet preferred mode scaling law
- Receptivity characteristics for J = 2 and 6
  - Pressure antinode → outer jet puffing mechanism
  - Scales with outer jet dynamic pressure
  - Pressure node → excitation of helical or antisymmetric mode
  - Very sensitive mode—driven by low level forcing

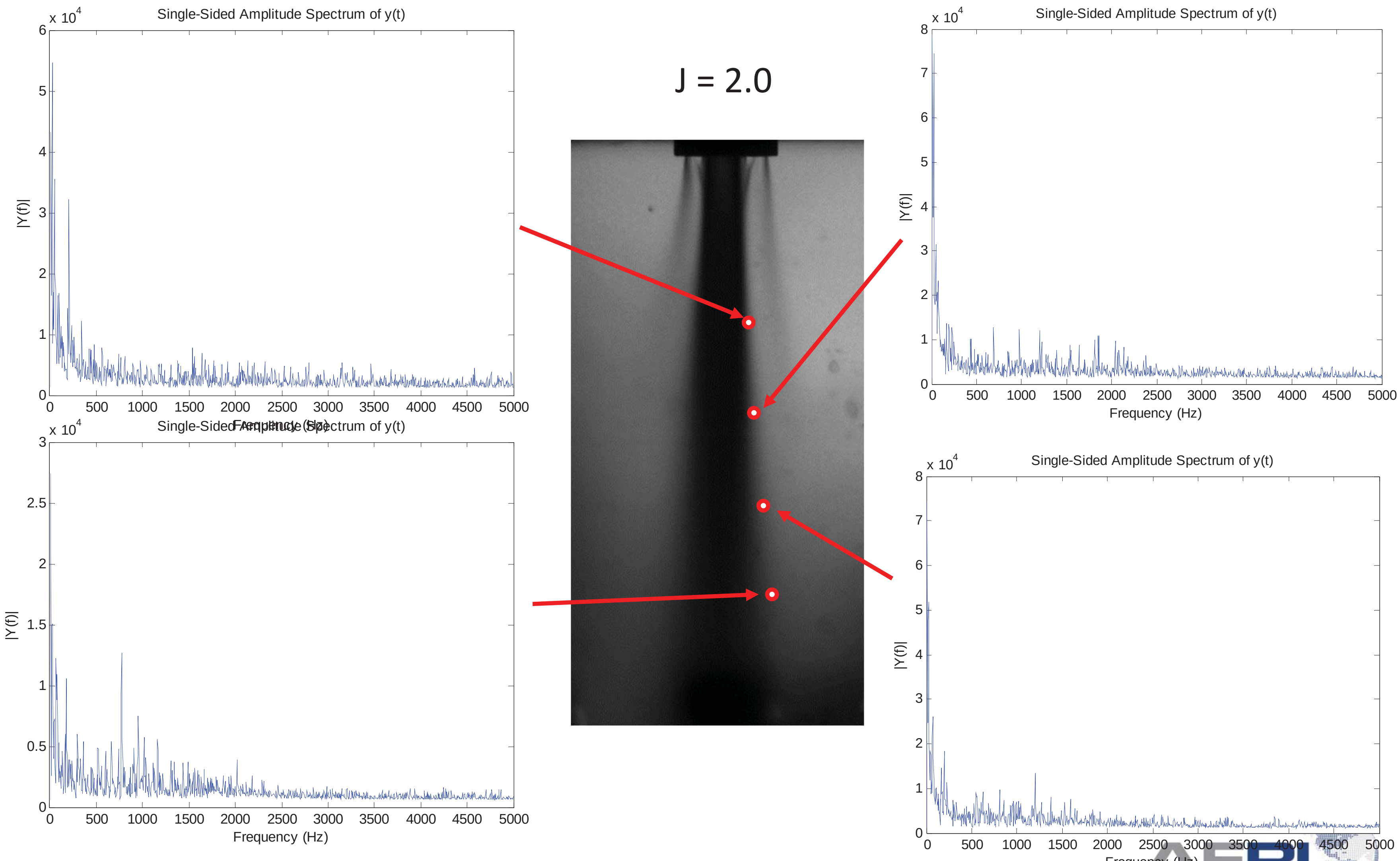
Future Work

- Determine robustness of scaling laws
  - Convection velocity (i.e. Dimotakis law)
  - Strouhal number
- Supercritical conditions
- Reacting flow conditions
- Multiple injectors

Backup slides

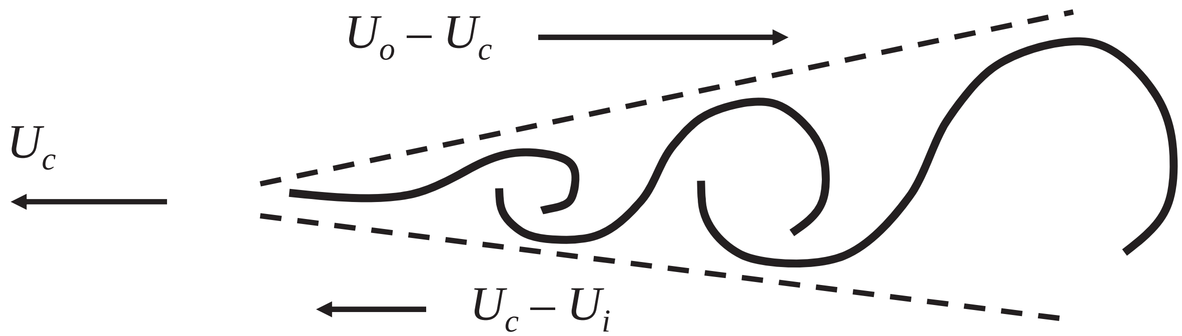
Unforced Coaxial Jets

- Frequency depends on location



Convection Velocity

Convective Shear Layer Velocity by Dimotakis (1986)
Vortex Frame of Reference



$(U_o > U_i)$

- Bernoulli's equation
  - A stagnation point must exist between vortices. Therefore, along a line through this point, dynamic pressures are approximately equal.

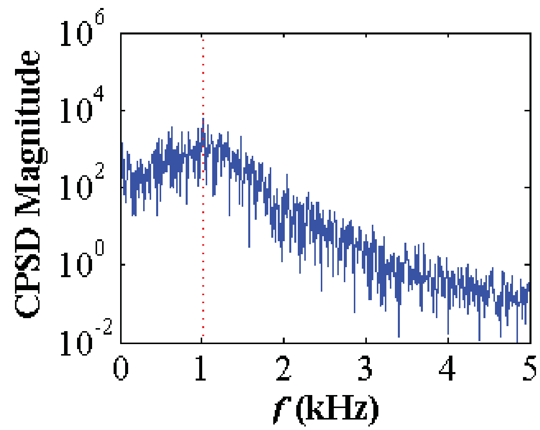
$$\rho_o (U_o - U_c)^2 \approx \rho_i (U_i - U_c)^2$$

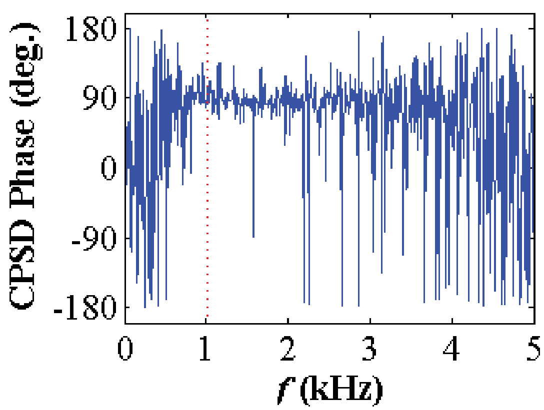
$$U_c = \frac{U_o \rho_o^{1/2} + U_i \rho_i^{1/2}}{\rho_o^{1/2} + \rho_i^{1/2}} \qquad St = \frac{f_{nat} D}{U_c}$$

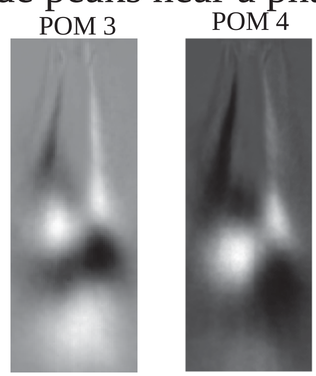
⟹ If St, D, U_c are held constant then f_{nat} may be constant.

Convective Mode from POD

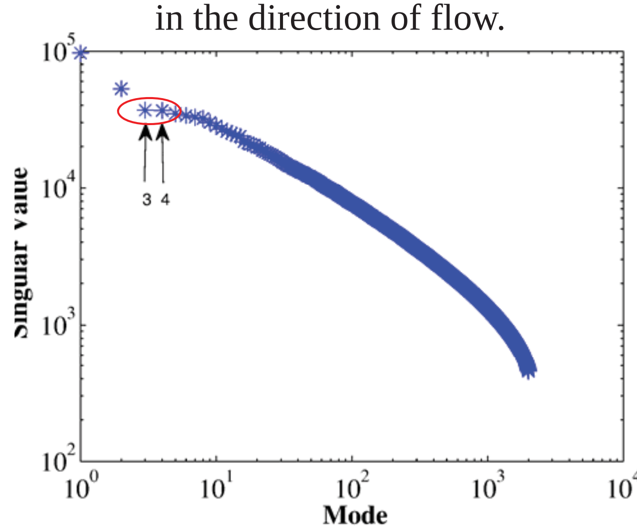
- Proper Orthogonal Decomposition
  - To identify traveling, coherent structures, a conjugate mode pair is identified as any two modes whose CPSD magnitude peaks near a phase of ±90°.[12]







POMs 3 & 4 exhibit the same flow structure, shifted by 90° in the direction of flow.



Proper orthogonal modes (POMs) 3 & 4 were found to be the **most energetic conjugate pair.**

The natural mode is represented by POMs 3 & 4.

The natural mode spans a band of frequencies rather than a single peak frequency.

Arienti, M. and Soteriou, M.C.(2009)